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# Operating Guidelines
## for
# the Airborne Radar Test-System
[Unclassified Title]

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April 1971

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Washington, D.C.

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# OPERATING GUIDELINES FOR THE AIRBORNE RADAR TEST-SYSTEM

## (Unclassified Title)

## ABSTRACT

## (Secret)

A scaled radar test-system is being flown in an EC-121 air-
craft to investigate some of the problems associated with ocean
surveillance. This test-system has been scaled so that its perform-
ance will simulate that of a satellite-borne ocean-surveillance radar
orbiting at an altitude of 200 nautical miles. This report provides
some operational guidelines which will aid in obtaining meaningful
data from the system. Curves and charts are presented which will:
(1) permit the selection of grazing angle; (2) indicate the properly-
scaled values for antenna rotation rate and transmitter power; and
(3) show the limits of operation as a function of radar altitude and
target range.

## PROBLEM STATUS

This is an interim report on the problem; work is continuing.

## AUTHORIZATION

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## (Unclassified)

OPERATING GUIDELINES FOR THE AIRBORNE RADAR TEST-SYSTEM

(Unclassified Title)

INTRODUCTION

(S)   The Aerospace Radar Branch is currently engaged in a series
of tests, the purpose of which is to investigate some of the problems
associated with ocean surveillance from a satellite-borne radar
system.   These tests are being conducted with an airborne test-system
which was designed and assembled by the Branch.   The design of this
airborne radar was based on a satellite reference system whose per-
formance characteristics were scaled so that the resulting model
could operate from one of the Laboratory's EC-121 aircraft at an alti-
tude of 15,000 feet.   The principles upon which this scaling tech-
nique was based are described in a recent NRL report[1].

(S)   Because of problems associated with the rather large
altitude scaling factor between satellite and aircraft (a ratio of
81:1), the test-system could be designed to match the performance of
the reference system for targets lying at only two specific values
of grazing angle.   It was realized of course that, because of the
usual operational difficulties encountered in flight, it would gen-
erally not be possible to position the target at the precise values
of grazing angle for which the system had been designed.   Therefore,
the referenced report included an analysis of the effect which range
and azimuth errors would have on the accuracy of the scaled data.
It was found that if reasonable care were taken in positioning the
aircraft in relation to the target, accurate performance data could
be obtained with the test-bed radar system.

(U)   With the commencement of operational flights, it becomes
apparent that an extension of this error analysis is necessary to
take into account what the effect will be on the resultant data when
the radar is operated at altitudes other than that for which the
scaled system had been designed.   Although a specified aircraft alti-
tude, once reached, can usually be controlled by the pilot to within
±30 feet, situations can arise in which weather conditions or inter-
fering aircraft traffic make it impossible to operate at the design-
altitude of 15,000 feet.   Therefore, it will be a major purpose of
this report to delineate the permissible regions of operation for
various altitudes of the radar.   At the same time, the opportunity
will be taken to update the parameters of the test radar to reflect
actual values rather than the design values which were used in the
previous error analysis.   Furthermore, tables will be presented which
show the levels of transmitter r.f. pulse power required to simulate

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the sensitivity of the reference system for various combinations of altitude and range in the test-bed system. Finally, some simple but useful curves will be provided which should be of aid in carrying out the tests.

## PARAMETERS OF THE AIRBORNE TEST-SYSTEM

(S) The airborne radar test-system is actually composed of two sub-systems. One sub-system is used for obtaining data on targets at shallow grazing angles; the other, for targets at steep grazing angles. The only difference in hardware between the two sub-systems is that different antennas are used; all other radar components (transmitter, receiver, data processor) are used in common. With respect to parameters other than those of the antennas, the sub-systems use different values of pulse repetition frequency and will require different levels of transmitter power. The parameters for the two subsystems are listed in Table I.

## CONSIDERATIONS OF GRAZING ANGLE

(S) In the design of the test-bed radar system, the performance was scaled for two discrete values of grazing angle: 1.5° for the shallow-grazing-angle sub-system, and 28° for the steep-grazing-angle-sub-system. However, in judging the validity of test data obtained under various operational conditions, it is not necessary that consideration be restricted to a predetermined value of grazing angle. For example, if a change in radar altitude should degrade the performance of the system at a grazing angle of 1.5 degrees, but result in satisfactorily scaled performance at a grazing angle of 1.1 degrees, then the test results will be quite acceptable. The basic aim of the test program is to investigate surveillance capabilities in regions of shallow (i.e., about 1.5°) and of steep (i.e., about 28°) grazing angle, and as long as the regions of acceptable scaling do not depart too drastically from these nominal values, valid and meaningful data will be obtained. Therefore, the technique which will be used in the computer-aided analysis which follows will be this: Critical performance factors of the airborne test-system will be calculated as a function of grazing angle for a series of aircraft altitudes. These same performance factors will be calculated for the satellite reference system (at a constant altitude of 200 nautical miles) using the same increments of grazing angle. The computer program will also calculate and print out the discrepancies in these performance factors between the two systems. Then, for whatever limits of error we wish to establish, this printout will show the range of grazing angle over which

## TABLE I

### SUBSYSTEM PARAMETERS

| Parameter | Subsystem for Steep Grazing Angles | Subsystem for Shallow Grazing Angles |
|---|---|---|
| Frequency | 1230 MHz | 1230 MHz |
| Pulse Length | 0.1 μsec | 0.1 μsec |
| PRF * | 62.5 pps | 39.0 pps |
| Pulse Compression Ratio | 200:1 | 200:1 |
| Antenna Beamwidths * | | |
|     Horizontal | 44 degrees | 10.7 degrees |
|     Vertical | 38 degrees | 19.5 degrees |
| Antenna Polarization | Horizontal | Horizontal |
| Depression Angle of Antenna Beam Center * | 26 degrees | 1 degree |
| Antenna Gain * | 13.3 dB | 22.2 dB |

\* measured values, which differ slightly from previously
used design values.

operation of the test system will yield valid data. The results
will then be plotted in a form which should lead to an appreciation
of the scaling limitations of the airborne radar test-system.

### PERFORMANCE FACTORS TO BE CONSIDERED

(U) The performance factors which can be expected to change
with a change in radar altitude are:

    (a) the size of the clutter cell

    (b) the signal-to-noise ratio (for a given target size)

    (c) the number of pulses integrated

    (d) sea clutter decorrelation time

    (e) target decorrelation time and the number of independent samples.

Each of these factors will now be considered in detail.

(U) _The size of the clutter cell_: Fig. 1 illustrates a patch of the surface of the sea illuminated by the radar. This patch is sometimes referred to as the "resolution cell"; its dimensions define the basic resolution limits of the radar. It is also referred to as the "clutter cell" because its size determines the amount of sea clutter which will be backscattered to compete with the signal returned from the target.

(U) In order that the target occupy the same number of resolution cells in both systems, and that the magnitude and distribution of sea clutter be the same, this clutter-cell size should not change appreciably between the test and reference systems. The radial length of the cell on the surface of the sea is

$$r_\rho = \frac{c\ \tau}{2}\ \sec\ \phi \tag{1}$$

in which c is the velocity of light, $\tau$ is the pulse length, and $\phi$ is the grazing angle. The dimension $r_\rho$ can be preserved by keeping the same pulse length and by comparing data for identical values of grazing angle, which is what will be done. In the other dimension the width of the clutter cell is $R\theta$, where R is the radar slant-range to the target area and $\theta$ is the width of the radar beam. In the current investigation, for a given altitude of the airborne test-system, the clutter-cell width will be calculated for both test and reference systems at each value of grazing angle. Then the difference in cell width will be expressed as a percentage of the reference-system clutter cell; thus

$$\zeta = \frac{(R\theta)_{test} - (R\theta)_{ref}}{(R\theta)_{ref}} \times 100\% \tag{2}$$

The limits for this error function will be chosen to be:

    a.   $\xi$ =  '10% - the preferred region of operation

    b.   $\xi$ = $\pm$20% - an acceptable region for operation

    c.   $\xi$ > '20% - not acceptable for operation

    (U)   The value of $\theta$ in Eq. (2) depends on the position of the target with respect to the elevation plane of the radar beam. If the target is located at the depression angle at which the beam is pointed, $\theta$ will be the principal-plane half-power azimuth beamwidth of the antenna (10.7° for the shallow-grazing-angle subsystem; 44° for the steep-grazing-angle subsystem). At other depression angles the effect of the antenna elevation pattern must be taken into account. The value of $\theta$ can be determined by considering the elliptical cross-section of the beam as shown in Fig. 2. The beam is located with its principal azimuth plane (beamwidth = $\theta_o$) along the X-axis, and its principal elevation plane (beamwidth = $\gamma_o$) along the Y-axis. The equation for the ellipse is:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \tag{3}$$

in which:

$$a = \tfrac{1}{2} \text{ the minor axis of the ellipse} = \theta_o/2 \tag{4a}$$

$$b = \tfrac{1}{2} \text{ the major axis of the ellipse} = \gamma_o/2 \tag{4b}$$

We wish to find the effective azimuth beamwidth, $\theta$, at an angle $\beta$ from beam center. In Eq. (3):

$$x = \theta/2 \tag{5a}$$

$$y = \beta = (\psi_o - \psi) \tag{5b}$$

where $\psi_o$ is the depression angle corresponding to the center of the beam, and $\psi$ is the depression angle corresponding to slant range R (in Eq. (2)). Substituting Eqs. (4) and (5) into (3) and solving for $\theta$:

$$\theta = \theta_o \sqrt{1 - \frac{4(\psi_o - \psi)^2}{\gamma_o^2}} \qquad (6)$$

(S) <u>Signal-to-noise ratio</u>: In order that the performance of
the airborne test system be meaningfully related to that of the satel-
lite reference system, it is necessary that comparable levels of sig-
nal be received and processed, i.e., that the signal-to-noise ratios
be the same in both systems for a given-size target. The signal-to-
noise ratio (or, more precisely, the signal-to-<u>noise-plus-clutter</u>
ratio) is a function of a number of radar parameters, chief of which
are: transmitted power, antenna gain, receiver noise figure, re-
ceiver bandwidth and frequency. Values for most of these parameters
have already been established on the basis of other considerations[1].
However, the transmitted r.f. power can be adjusted to achieve the
desired level of signal with respect to noise and clutter, provided
that the transmitter offers an adequate range of adjustment. If this
adjustment is not sufficient, the effect of changing transmitter power
can be simulated by inserting attenuation in the receiving line just
before the r.f. amplifier. By whichever means this power-level set-
ting is accomplished, the adjustment can be made to accommodate any
desired combination of system parameters. Therefore, consideration
of this factor will be delayed until all other scaling problems have
been settled.

(U) <u>Number of pulses integrated</u>: In order to achieve equal
post-detection integration gains in both test and reference systems,
the number of pulses integrated should be the same. The number of
pulses integrated in the test system is given by

$$n = \left(\frac{\theta}{\omega}\right) (PRF) \qquad (7)$$

in which $\theta$ is the effective width of the radar beam (as given by
Eq. (6)) and $\omega$ is the rotational velocity of the antenna. In the
original design of the test-system the desired number of pulses
integrated was obtained for each of the two sub-systems by making an
appropriate selection of values for both antenna rotation speed <u>and</u>
the pulse repetition frequency (PRF). This extra degree of freedom
was advantageous because these parameters also produced effects on
other performance factors. However, with the present configuration
of the radar, PRF values have been established and cannot easily be

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altered. Therefore, any adjustment required in the value of n will have to be made by changing the antenna rotational speed, ω. Operationally, this is a convenient adjustment to make, since the antenna-control system provides for continuous control of antenna speed over a wide range of values.

(U) <u>Sea-clutter decorrelation time:</u> The improvement in detection achieved through integration depends on the fact that the noise component of the received signal is not correlated. In the same manner, the target signals will be enhanced relative to the signals from the surrounding sea, provided that this sea return is decorrelated from pulse to pulse. If the time required for the sea clutter to decorrelate is short in terms of the interpulse period, the clutter has a noiselike character and will have a similar effect in the integration process as does noise. If, on the other hand, the sea clutter remains correlated for a full interpulse period or longer, the character of the clutter will be more like that of the signal itself, and the full improvement from integration will not be realized.

(S) Sea-clutter decorrelation in terms of interpulse periods is given by the "clutter product": $T_d$ x (PRF), where $T_d$ is the sea-clutter decorrelation time in seconds and the Pulse Repetition Frequency is given in pulses per second. In the satellite reference system this clutter product is equal to 0.211 indicating that sea clutter is completely decorrelated from pulse to pulse (because the product is less than unity). In order to achieve comparable performance in the airborne test-bed system, it is a sufficient condition that:

$$T_d \text{ x (PRF)} < 1 \tag{8}$$

In the design of the test-system, the clutter product was 0.560 for the case of the shallow-grazing-angle sub-system and 0.211 for the case of the steep-grazing-angle sub-system. Therefore, in the current analysis, it is necessary to determine whether changes in the parameters affecting this clutter product can make it increase beyond the limit expressed by Eq. (8). By substituting an approximate expression for sea-clutter decorrelation time, Eq. (8) can be rewritten as:

$$\frac{\lambda}{V\theta} \text{ x (PRF)} < 1 \tag{8a}$$

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where $\lambda$ is the radar wavelength, V is the linear velocity of the
radar platform (i.e., the aircraft), and $\theta$ is given by Eq. (6). In
Eq. (8a) $\lambda$ and the PRF remain constant. The effective beamwidth, $\partial$,
will vary with grazing angle and will thus cause changes in the
clutter product. A change in aircraft ground speed with respect to
its nominal value of 311 feet per second will also change the clutter
product. Assuming winds of 30 knots, aircraft velocity might be in
error by as much as 20%. The effects of these variations in $\theta$ and V
will have to be considered in the computer program for establishing
the operating limits of the airborne test-system.

(U) <u>Target decorrelation time and the number of independent
samples</u>: Since a ship target comprises a number of individual
scatterers, the cumulative signal returned from the ship will depend
on the way in which the returns from these numerous scatterers add
in phase and amplitude. The degree to which the target-returns from
successive radar pulses will be correlated depends on both the change
in the viewing angle (due to motion of the platform) and the motion
of the target itself during the interpulse period. These effects can
be expressed in terms of a target decorrelation time, a concept which
is analagous to the sea-clutter decorrelation time previously dis-
cussed. Total target decorrelation time is given by[1]:

$$T_t = \frac{T_p \cdot T_s}{T_p + T_s} \tag{9}$$

in which:

$T_s$ = target decorrelation due to ship motion
(assuming sea state 4)

= 1 second at steep grazing angles[*]

= 100 seconds at shallow grazing angles[*]

$T_p$ = target decorrelation due to motion of the
radar platform

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[*] These estimates are based on a private communication with
Dr. G. Trunk, Radar Analysis Staff, NRL

$$T_p = \frac{R\lambda}{2\ Vs} \tag{10}$$

$\lambda$ = radar wavelength

R = slant range to target

V = radar platform velocity

s = length of ship target

(U)  The value of $T_t$ affects the number of independent samples received by the radar during the viewing (i.e., integration) period. The number of independent samples is

$$N = \frac{I}{T_t} + 1 \tag{11}$$

in which I, the integration period in seconds, is given by

$$I = \frac{\theta}{\omega} \tag{12}$$

(U)  Table II illustrates how the value of N is related to system performance[2]. It would be advisable of course, that the value of N be the same in both test and reference systems. This however, was not possible even in the original design of the test-system because of conflicts between various performance requirements. In the current situation, the parameters $\theta$ and $\omega$ have already been established on the basis of previous considerations and therefore cannot be used to adjust the value of N. Therefore, in the present analysis, the value of N will simply be calculated for each parametric change to determine whether the resultant difference in sensitivity between the test and reference systems is acceptable. The criteria for acceptability will be the same ones used in the previous analysis[1]: The sensitivity of the steep-grazing-angle subsystem shall be within +0.5 dB of that of the reference system; the sensitivity of the shallow-grazing-angle subsystem shall be within +0.5 dB and -2.0 dB of the reference system.

RESULTS OF THE ANALYSIS

(U)  From the computer printout of the performance factors and error factors discussed in the previous paragraphs, the limits of

TABLE II

Required Increase In The Signal-to-Noise Ratio
With Respect To Complete Independence

| Number Of Independent Samples | Increase in Signal-to-Noise Ratio (in DB) | |
|---|---|---|
| | For 90% Probability of Detection | For 99% Probability of Detection |
| 1 | 7.5 | 11.75 |
| 2 | 4.5 | 7.25 |
| 4 | 3.0 | 4.75 |
| 10 | 1.25 | 2.0 |
| 100 | 0 | 0 |

system operation can be delineated. The results have been plotted in Fig. 3 for the shallow-grazing-angle subsystem and in Fig. 4 for the steep-grazing-angle subsystem. In both cases, the chief parameter which determined these operating regions was the factor $\xi$, the percentage error in clutter-cell width as given by Eq. (2). The other performance factors were checked and found to be within acceptable limits in these regions.

(U) These curves provide other useful guides for the operation of the test radar. Thus, in Fig. 3 the contours of constant grazing angle are shown for the shallow-grazing-angle subsystem. By selecting an appropriate altitude and controlling the flight path so that the range to the target is within the acceptable region, radar data can be gathered for any desired value of grazing angle from 0° to 2.0°. Contours of constant rotation rate, $\omega$, are also shown in Fig. 3. It can be appreciated from the values of $\omega$ shown on these curves, that this is not a particularly critical parameter for this subsystem. Over the entire operating region the value of $\omega$ does not vary more than ±3% from a nominal value of 1.9 degrees per second.

(U) For the case of the steep-grazing angle subsystem, the operating regions delineated in Fig. 4 show that there is a minimum altitude for gathering meaningfully-scaled data. Thus, to take

advantage of the preferred region of operation, the aircraft must
fly at altitudes above 14,000 feet. Contours of constant $\omega$ are also
shown in Fig. 4. Because of the geometrical relationship between
radar and target in this subsystem, the contours of constant grazing
angle coincide with contours of constant $\omega$. In order to avoid con-
fusion in the diagram, only the contours of integer values of $\omega$ have
been drawn, but these have also been labeled with the resultant
(noninteger) values of grazing angle. Although the plot here shows
a preferred region extending out as far as 12.5 nautical miles (for
an altitude of 16,000 feet), in general, it will be the area close
to the left edge of the preferred region which will be utilized.
This will be consistent with one of the basic aims of the tests,
which is to examine surveillance capabilities at steep grazing angles
where system sensitivity is clutter limited.

(U)  As an example of how these curves would be used during a
data-gathering flight, refer to Fig. 4. Suppose that for operational
reasons the airplane must fly at an altitude of 14,000 feet. The
shaded bands of Fig. 4 show that the range to the target must lie be-
tween 4.1 and 10.2 nautical miles, if meaningfully scaled data are to
be obtained. At this altitude, the performance of the test system
will most closely simulate that of the reference system if the target
is at a range of about 6.2 nautical miles (when it is broadside to
the flight vector), since this point lies within the "preferred" re-
gion of operation. However, a more important consideration would
probably be to gather data in regions where the sea-clutter return
is high. Therefore, we might choose to take data where the grazing
angle is steeper, say at a grazing angle of 27.5 degrees. The 27.5
degree line in Fig. 4 shows that if we wish to operate at this point
we must set the antenna speed at 36 degrees/second and adjust the
aircraft flight path so that the target will be at a range of 4.5
nautical miles as the plane passes by it.


R.F.  POWER REQUIREMENTS

(S)  As mentioned earlier, the signal-to-noise ratio of the
satellite reference radar will be simulated in the airborne test sys-
tem by an appropriate adjustment of transmitter power output. The
level of r.f. power required for this simulation can be calculated
from the basic radar equation. A computer program was set up to per-
form these calculations using the equations which are detailed in
Appendices A and B. A flow chart of the computer program is pre-
sented in Appendix C.

(U)  The results of these power calculations are shown in Fig.
5 for the shallow-grazing-angle subsystem and in Fig. 6 for the

steep-grazing-angle subsystem. Values of r.f. pulse power are shown
for increments of altitude and range in the areas of interest. The
charts also reflect the regions of operation which were delineated in
Figs. 3 and 4, the various shaded regions having the same meaning as
before. The fact that transmitter pulse power, rather than average
power, was selected as the parameter for display is simply a matter
of operational convenience.

(U)  The power levels shown in Figs. 5 and 6 are for measure-
ments made at the directional coupler. These levels are therefore
0.8 dB lower than the actual transmitter output because of the inter-
vening line loss. If the adjustment available at the transmitter
proves to be inadequate for lowering the signal to the desired level,
known values of attenuation can be inserted in the receiver line
(before the r.f. amplifier) to further decrease system sensitivity.

## TRACK-AID CONTOURS

(U)  In order to make proper use of the foregoing guides, the
aircraft flight-path should be oriented so that the target will be at
the selected radar range when its bearing is 90 degrees from the air-
craft flight vector. This situation will be referred to as the
"broadside aspect". This broadside situation is the "design center"
in regard to various scaling considerations. For target angles other
than the broadside aspect, scaling is less perfect, although, as has
been shown previously[1], the scaled performance will be quite adequate
over a considerable range of aspect angles. However, in order to
minimize scaling errors, the aim during a data-pass should be to ac-
hieve the intended radar-to-target range for the broadside aspect.

(U)  For this purpose the Track-Aid contours of Figs. 7 and 8
have been drawn. Based on the simple geometric relationship between
radar-to-target aspect-angle and range, the plots trace the apparent
path of a target as the radar passes by. For example, suppose one
were to sight a target at a range of 60 nautical miles at 90° (broad-
side) aspect. Then, assuming a constant aircraft flight vector, the
track of this target in range and bearing would follow the curve
labled "60". However, it is actually the converse situation in which
these curves find their utility. That is, in order to achieve a
specified range at broadside, one must adjust the aircraft flight
path until the target lies on the desired contour; thereafter, if the
flight vector is held constant, the target-track will follow the se-
lected contour. The way in which these curves can be utilized during
an operational flight is illustrated with reference to Fig. 7. Sup-
pose that on the approach the target is located at a bearing of 54°
(from the nose of the aircraft) and a range of 84 nautical miles.

This position of the target is plotted in Fig. 7 at the intersection of the 54-degree abscissa with the 84-nautical-mile ordinate. This point, marked "A" in Fig. 7, lies on the 68-nautical-mile contour. However, suppose it had been desired on this data run that the target be at a range of 60 nautical miles at broadside aspect. One must then (by a suitable maneuver of the aircraft) shift the target from the 68-nautical-mile contour to a position on the 60-nautical-mile contour, or from point A to some point such as B in Fig. 7. It is not possible nor is it necessary, to describe here the precise aircraft maneuver which is required to accomplish this change between contours. This task may best be left to the pilot, who should be able to make the desired adjustment of the flight vector upon being given an instruction to "execute an S-turn to increase range by eight nautical miles".

## SUMMARY

(U)  Calculations have been made and a number of aids have been presented which will prove useful in the operation of the airborne test-bed radar system.  The curves and charts will:

   (1)  permit the selection of grazing angle

   (2)  indicate the proper value of antenna rotation speed

   (3)  show the limited regions of operation

   (4)  indicate the proper setting of transmitter power

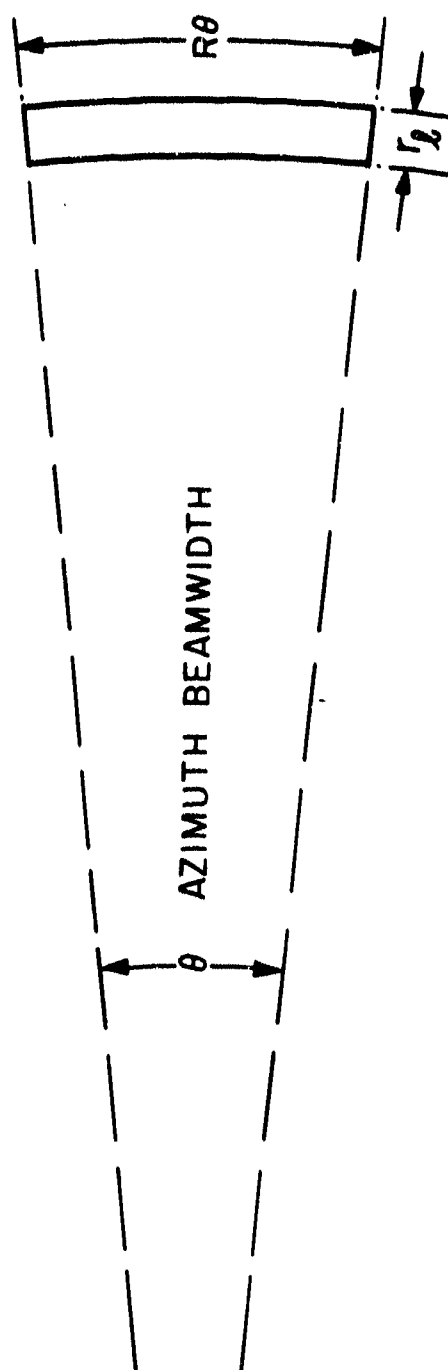   (5)  provide assistance in orienting the aircraft flight
        vector.

Fig. 1 - The radar clutter cell on the surface of the sea. The length of the cell in the radial direction is $r_l$ , and the width of the cell at range R is R$\theta$.
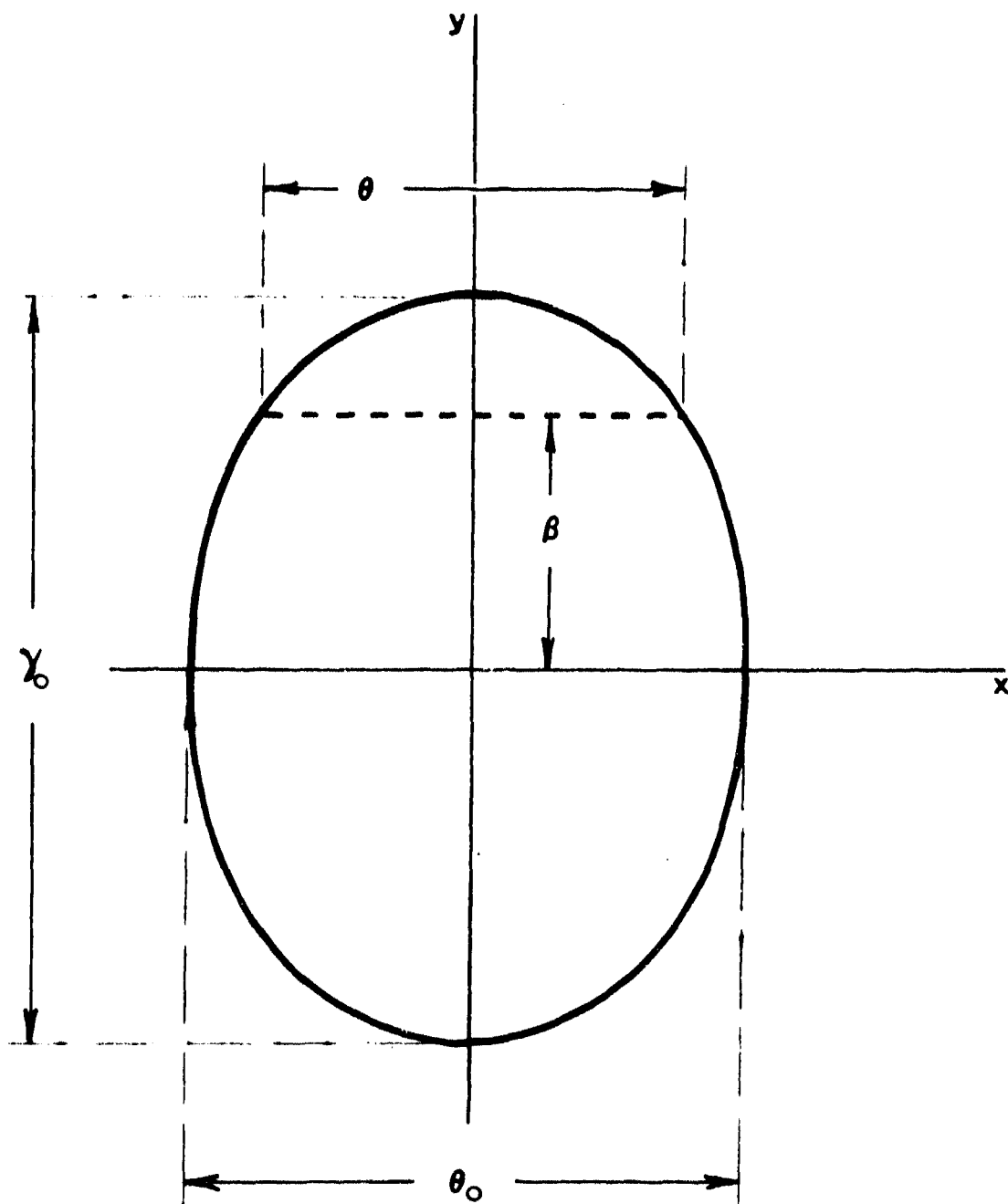
Fig. 2 – Elliptical cross-section of the radar beam. The principal-plane beamwidths are $\theta_0$ (in azimuth) and $\gamma_0$ (in elevation). $\theta$ is the (azimuth) width of the beam at angle $\beta$ from the elevation axis.
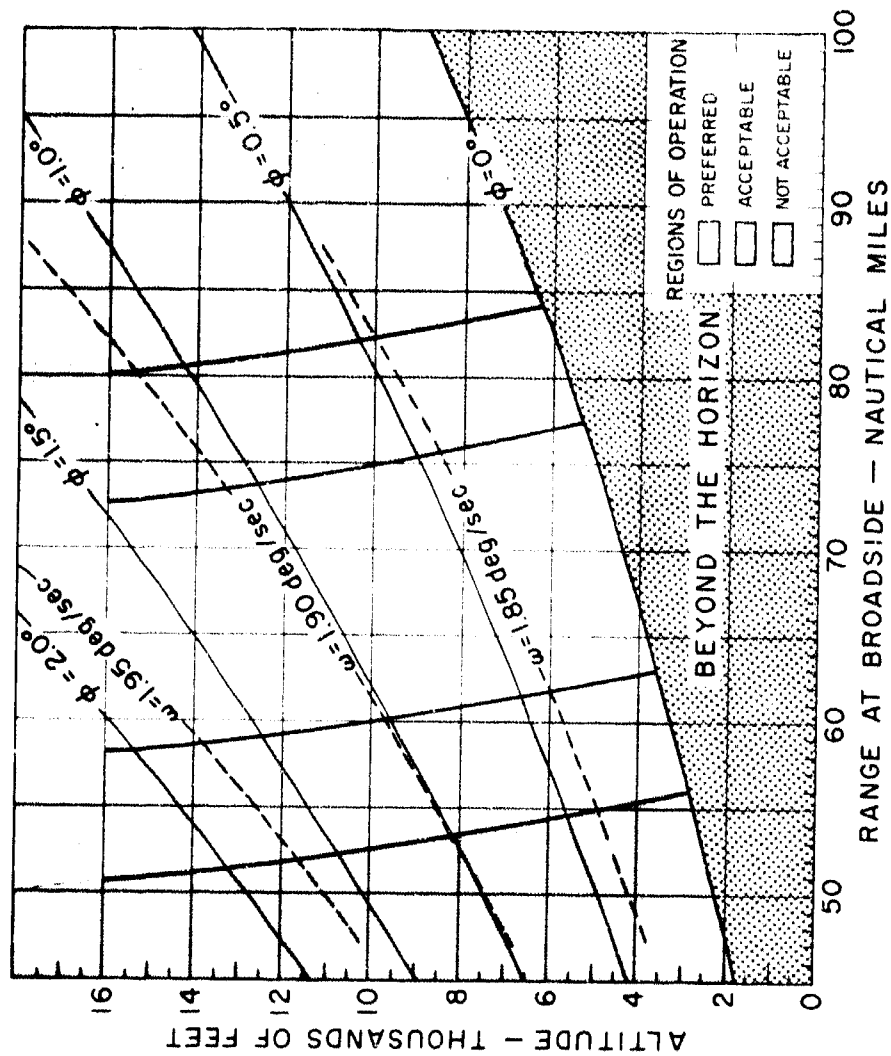
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Fig. 3 – Operating regions and parameters for the shallow-grazing-angle subsystem. $\phi$ is the grazing angle; $\omega$ is the antenna rotation speed.
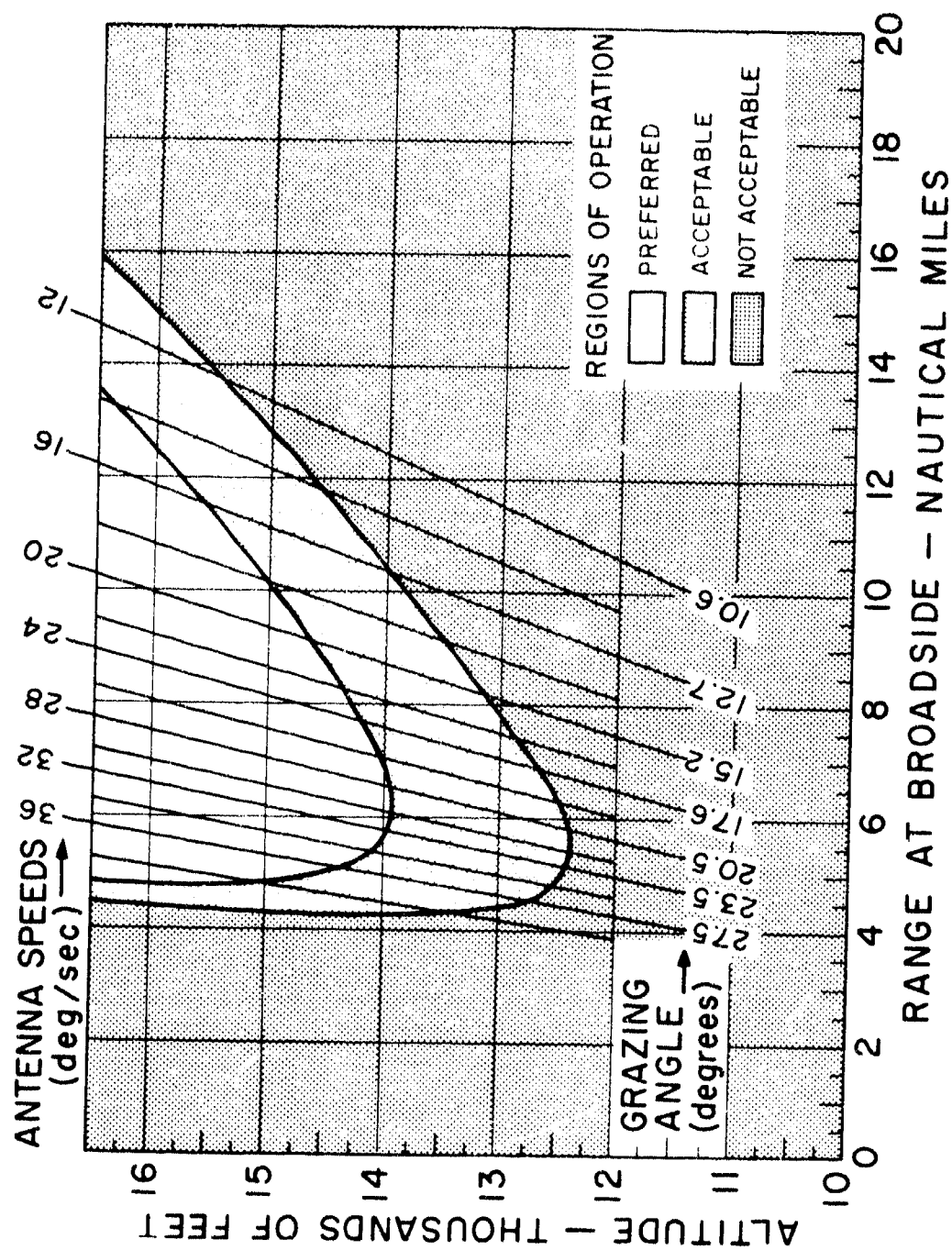
Fig. 4 – Operating regions and parameters for the steep-grazing-angle subsystem. Contours of Antenna Speed are coincident with contours of Grazing Angle.

POWER IN KW TARGET SIZE = 200 SQUARE METERS 22 March 1971 (DATE)

| ALTITUDE (feet) | RADAR RANGE TO TARGET (nautical miles) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 52 | 54 | 56 | 58 | 60 | 62 | 64 | 66 | 68 | 70 | 72 | 74 | 76 | 78 | 80 | 82 |
| 16,000 | 2.80 | 3.25 | 3.84 | 4.41 | 5.05 | 5.76 | 6.54 | 7.58 | 8.55 | 9.62 | 10.78 | 12.05 | 13.81 | 15.37 | 17.06 | |
| 15,000 | 2.77 | 3.21 | 3.81 | 4.38 | 5.02 | 5.72 | 6.49 | 7.54 | 8.51 | 9.58 | 10.74 | 12.01 | 13.78 | 15.34 | 17.04 | |
| 14,000 | 2.74 | 3.18 | 3.78 | 4.35 | 4.98 | 5.68 | 6.45 | 7.51 | 8.48 | 9.54 | 10.70 | 11.97 | 13.76 | 15.32 | 17.01 | |
| 13,000 | 2.71 | 3.15 | 3.75 | 4.32 | 4.95 | 5.65 | 6.42 | 7.48 | 8.45 | 9.51 | 10.67 | 11.93 | 13.75 | 15.31 | 17.00 | |
| 12,000 | 2.69 | 3.12 | 3.72 | 4.29 | 4.92 | 5.62 | 6.39 | 7.46 | 8.42 | 9.48 | 10.64 | 11.90 | 13.74 | 15.30 | 16.99 | |
| 11,000 | | 3.10 | 3.70 | 4.27 | 4.89 | 5.59 | 6.36 | 7.44 | 8.40 | 9.46 | 10.62 | 11.88 | 13.74 | 15.30 | 16.99 | |
| 10,000 | | 3.08 | 3.68 | 4.25 | 4.87 | 5.57 | 6.33 | 7.42 | 8.38 | 9.44 | 10.60 | 11.86 | 13.74 | 15.30 | 17.00 | 18.83 |
| 9,000 | | 3.06 | 3.67 | 4.23 | 4.86 | 5.55 | 6.31 | 7.41 | 8.37 | 9.43 | 10.58 | 11.85 | 13.75 | 15.31 | 17.01 | 18.84 |
| 8,000 | | 3.05 | 3.66 | 4.22 | 4.84 | 5.53 | 6.30 | 7.40 | 8.36 | 9.42 | 10.58 | 11.84 | 13.76 | 15.33 | 17.02 | 18.86 |
| 7,000 | | 3.03 | 3.65 | 4.21 | 4.83 | 5.52 | 6.28 | 7.40 | 8.36 | 9.42 | 10.57 | 11.83 | 13.78 | 15.35 | 17.05 | 18.89 |
| 6,000 | | | 3.64 | 4.20 | 4.82 | 5.51 | 6.27 | 7.40 | 8.36 | 9.42 | 10.57 | 11.84 | 13.81 | 15.38 | 17.08 | 18.92 |
| 5,000 | | | 3.64 | 4.19 | 4.82 | 5.50 | 6.27 | 7.40 | 8.37 | 9.42 | 10.58 | 11.84 | 13.83 | 15.38 | 17.04 | 18.85 |

Fig. 5 – Transmitter pulse power (in kilowatts) for the shallow-grazing-angle subsystem.

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POWER IN WATTS     TARGET SIZE = 200 ___ SQUARE METERS     22 MARCH 1971 (DATE)

| ALTITUDE (feet) | RADAR RANGE TO TARGET (nautical miles) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 |
| 16,000 | 88 | 73 | 80 | 98 | 125 | 162 | 210 | 266 | 336 | 426 | 675 | 1044 | 1570 | 2234 | 3267 | 4544 |
| 15,500 | 68 | 63 | 74 | 93 | 120 | 158 | 206 | 261 | 334 | 426 | 683 | 1061 | 1600 | 2343 | | |
| 15,000 | 55 | 55 | 68 | 89 | 117 | 155 | 201 | 259 | 334 | 429 | 692 | 1081 | 1635 | | | |
| 14,500 | 45 | 51 | 64 | 85 | 114 | 153 | 198 | 258 | 335 | 433 | 704 | 1104 | | | | |
| 14,000 | 38 | 47 | 61 | 83 | 112 | 149 | 196 | 259 | 338 | 439 | 718 | | | | | |
| 13,500 | 34 | 44 | 59 | 81 | 111 | 147 | 196 | 261 | 343 | 447 | | | | | | |
| 13,000 | 31 | 41 | 57 | 79 | 108 | 146 | 198 | | | | | | | | | |
| 12,500 | | 39 | 55 | 78 | | | | | | | | | | | | |
| 12,000 | | | | | | | | | | | | | | | | |
| 11,500 | | | | | | | | | | | | | | | | |

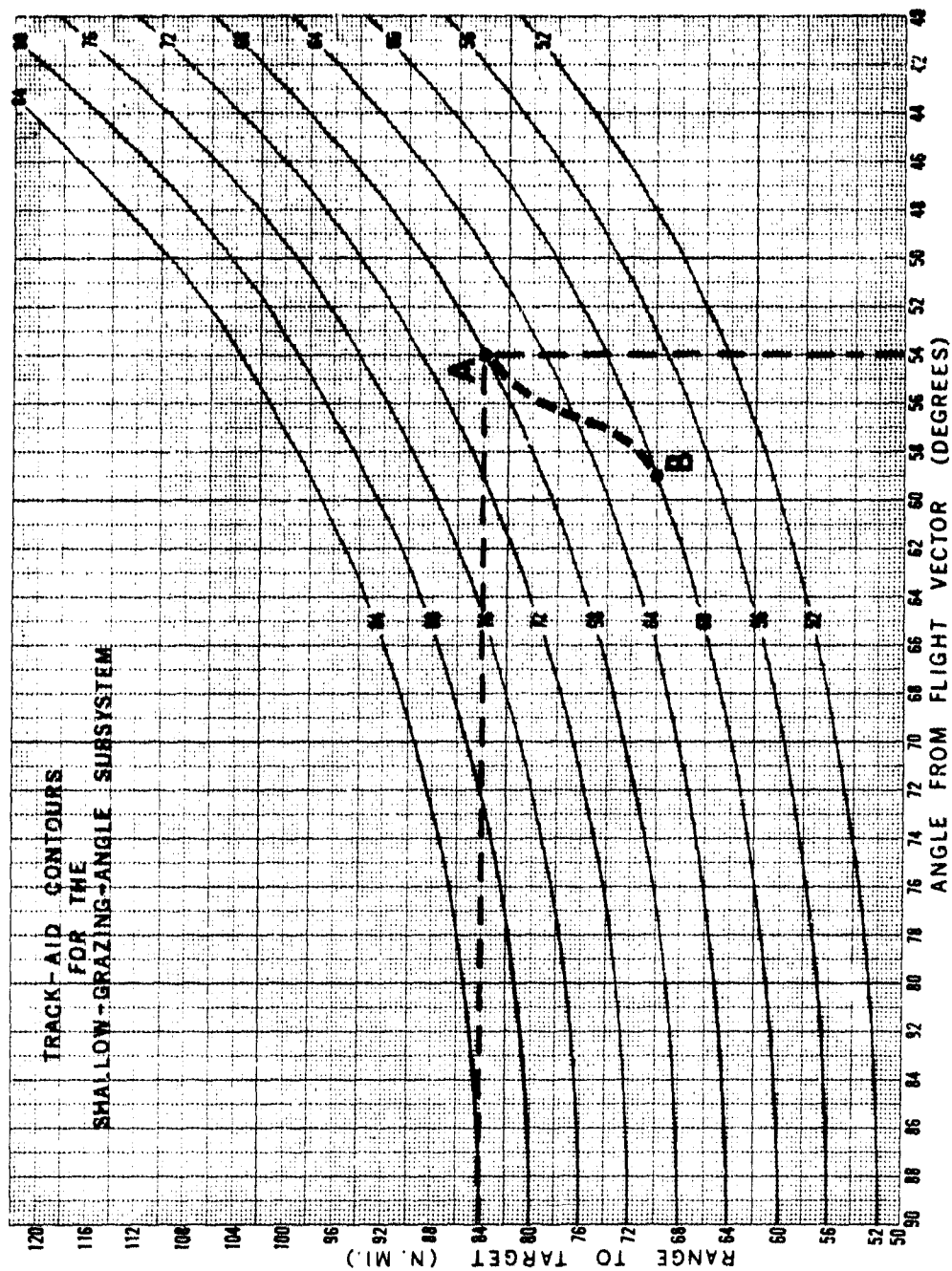Fig. 6 – Transmitter pulse power (in watts) for the steep-grazing-angle subsystem

Fig. 7 — Track-aid contours for the shallow-grazing-angle subsystem. If the target is at point A on the 68-nautical-mile contour, and it is desired that it be at a range of 60 nautical miles when it is broadside to the flight vector, the aircraft must be maneuvered to shift the position of the target to some point on the 60-nautical-mile contour such as B.
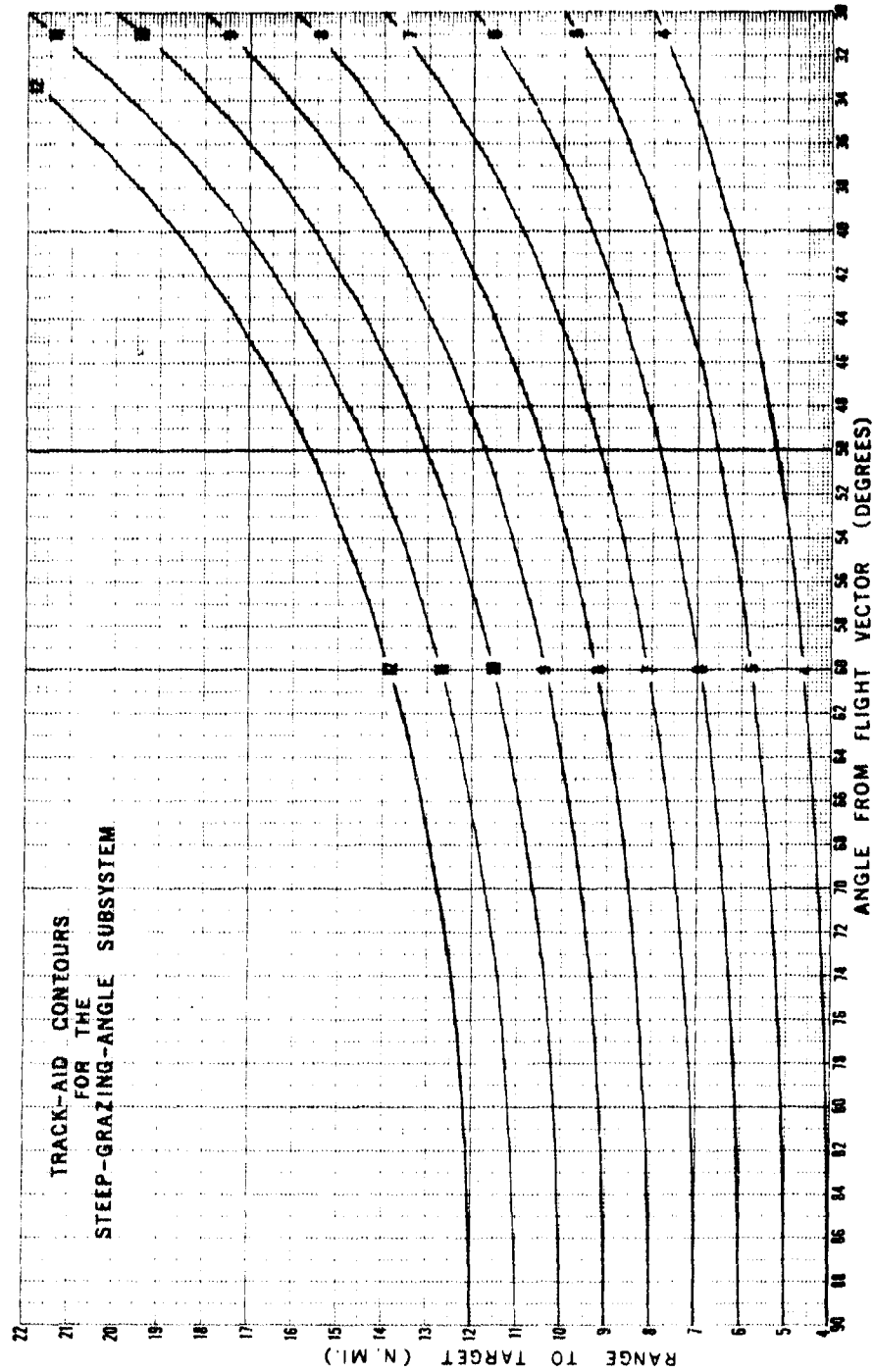
Fig. 8 – Track-aid contours for the steep-grazing-angle subsystem

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## APPENDIX A

## CALCULATION OF R.F.-POWER LEVELS

### INTRODUCTION

The levels of R.F.-power shown in Figs. 5 and 6 in the text were calculated in a computer program using a version of the basic radar equation. A flow chart of this computer program is shown in Appendix C. However, before presenting the form of the equation used in these calculations, certain parameters which appear as factors in the equation should be discussed in detail. These are:

(a) Antenna gain, G

(b) System transmitting losses, L

(c) Receiving system noise power, $N_o$

### ANTENNA GAIN, G

The values of antenna gain at beam center for the two subsystems were listed in Table I: 13.3 dB for the steep-grazing-angle system and 22.2 dB for the shallow-grazing-angle system. Since, in general, the target will not be located at the depression angle which corresponds to beam center, it is necessary to take into account the effect of the vertical pattern on antenna gain. For this purpose, the following function will be used to approximate the real antenna power pattern:

$$ G = \frac{\pi^4}{16} \left[ \frac{\cos^2 x}{\left[ \frac{\pi^2}{4} - x^2 \right]^2} \right] G_o \qquad (A-1) $$

where

$x = F \sin (\psi_o - \psi)$

$F =$ a factor relating to antenna size

$\psi_o =$ depression angle to beam center

$\psi =$ depression angle to target

$G_o =$ antenna gain at beam center

Equation (A-1) describes the pattern of a rectangular aperture with a cosine-tapered illumination and sidelobes of approximately 25 dB. In order to relate this gain function to the actual vertical power pattern, the factor F will be evaluated so that the theoretical relative gain matches the actual relative gain at the half-power points of the pattern. That is, the following equation is solved for F:

$$\frac{G}{G_0} = \frac{\pi^4}{16} \left[ \frac{\cos (F \sin \frac{\gamma_0}{2})}{\frac{\pi^2}{4} - (F \sin \frac{\gamma_0}{2})^2} \right]^2 = 0.5 \qquad (A-2)$$

in which $\gamma_0$ is the measured vertical half-power beamwidth of the antenna.

Equation (A-2) yielded F=11.03 for the shallow-grazing-angle subsystem, and F = 5.74 for the steep-grazing-angle subsystem. Using these factors, Equation (A-1) is then solved for antenna gain for the appropriate value of depression angle.

## SYSTEM TRANSMITTING LOSSES, L

The losses on transmission enter into the loss factor, L, in the denominator of the radar equation. Table A-1 lists these losses for both subsystems and notes (under "Justification") how the loss values were obtained. As indicated by the table, the tropospheric absorption is a constant for the steep-grazing-angle subsystem. However, at shallow grazing angles this loss factor does vary, both with grazing angle and with range. Table A-2 shows values for the tropospheric loss factor in the region of interest. These values were obtained from curves presented in Ref. 3. For determining the tropospheric loss in the computer program, equations were used which gave straight-line approximations to these values with grazing angle as the dependent variable.

## RECEIVING SYSTEM NOISE POWER, $N_0$

The losses in the receiving system are accounted for in terms of the receiving system noise power, $N_0$. Blake[3] discusses the concept of system noise temperature, which is related to system noise power by the equation:

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TABLE A-1

List of System Transmission Losses

| Loss | Symbol | Magnitude Of Loss | | Justification |
|------|--------|-------------------|---|---------------|
| | | Shallow-Grazing Angle Subsystem | Steep-Grazing Angle Subsystem | |
| Transmission Line* | $L_t$ | 1.75 dB | 1.75 dB | By Measurement |
| Antenna Pattern | $L_p$ | 1.60 dB | 1.60 dB | See Ref. 3 |
| Radome (Two-Way)** | $L_d$ | 1.00 dB | 1.00 dB | Calculated (See Ref. 4) |
| Tropospheric Absorption | $L_\alpha$ | See Table A-2 | 0.10 dB | From Fig. 22 in Ref. 3 |

\*   This is the transmission-line loss from the antenna
terminals to the directional coupler where the transmitter
power is monitored.

\*\*   To be rigorous, only one-half the total radome loss should
be applied here and the other half should be accounted for
in the receiving-system noise temperature calculation.  For
the sake of simplicity, however, the entire loss will be
applied here.

TABLE A-2

Two-Way Tropospheric Absorption (in DB) at 1230 MHz

| RANGE n. mi. | Grazing Angle | | | |
|--------------|------|------|------|------|
| | 0° | 0.5° | 1.0° | 2.0° |
| 50 | 1.05 | 0.95 | 0.90 | 0.80 |
| 60 | 1.20 | 1.15 | 1.05 | 0.90 |
| 70 | 1.40 | 1.30 | 1.20 | 1.00 |
| 80 | 1.60 | 1.45 | 1.30 | 1.10 |

$$T_s = \frac{P_n}{k\,B_n} = \frac{N_o}{k} \qquad\qquad (A-3)$$

In which:

$T_s$ = the overall receiving system noise temperature

$P_n$ = available noise power of the receiving system

$B_n$ = noise bandwidth of the receiver

$k$ = Boltzmann's constant = 1.3805 watt-sec/K°

$N_o$ = Noise power per unit bandwidth, the form of the parameter as it will be used in the radar equation.

As Blake shows, each of the components of the receiving system contributes its own effective noise temperature, so that the overall system noise temperature is

$$T_s = T_a + T_r + L_r T_e \qquad\qquad (A-4)$$

in which:

$T_a$ = antenna noise temperature

$T_r$ = transmission-line noise temperature

$L_r$ = transmission-line loss factor

$T_e$ = noise temperature of the receiver

We will now discuss each of these factors in detail.

Antenna Noise Temperature: If the sea is assumed to be a perfect (although not necessarily specular) reflector at 1230 MHz, then the effective noise-temperature contribution from the antenna is:

$$T_a = \frac{T_a' + 290\,(L_a - 1)}{L_a} \qquad\qquad (A-5)$$

in which:

$T_a{}'$ = temperature of extra-terrestrial noise sources as given by Fig. 11 in Ref. 3.

= 65° K for shallow grazing angles (i.e., approximately 1°)

= 22° K for steep grazing angles (i.e., approximately 25°)

$L_a$ = losses in the antenna, estimated to be 0.6 dB (or a loss factor of 1.15) for both subsystems

Substituting the appropriate values into Eq. (A-5) the resultant antenna noise temperature is found to be 94° K for the shallow-grazing-angle subsystem and 57° K for the steep-grazing-angle subsystem.

Transmission-Line Noise Temperature: For a transmission line with a loss factor of $L_r$, the noise temperature is:

$$T_r = 290 (L_r - 1) \tag{A-6}$$

The measured line loss between the antenna and the receiver in the test-bed system is 5.9 dB, corresponding to a loss factor of 3.89 (the antilog of 5.9/10). Using this value in Eq. (A-6), the transmission-line noise temperature is found to be 838° K (for both subsystems).

Noise Temperature of the Receiver: The effective noise temperature of a receiver with a noise factor of NF is:

$$T_e = 290 (\overline{NF} - 1) \tag{A-7}$$

The receiver currently being used in the airborne test-bed system has a noise figure of 4 dB, which corresponds to a factor of 2.51. Thus, from Eq. (A-7) the receiver has a noise temperature of 438°.

Overall System Noise Power: Substituting these component noise temperatures into Eq. (A-4), values for system noise temperature are found for each of the subsystems. The product of system noise temperature and Boltzmann's constant gives the overall system noise power per unit bandwidth, $N_o$. The results are listed in Table A-3.

TABLE A-3

System Noise Power

| Subsystem | System Noise Temperature in deg. K | Noise Power Per Unit Bandwidth in watt-sec |
|---|---|---|
| Shallow-grazing-angle | 2636 | $3.639 \times 10^{-20}$ |
| Steep-grazing-angle | 2599 | $3.588 \times 10^{-20}$ |

## THE CALCULATION OF R.F. POWER

We are now ready to present the equations used to calculate the r.f. power required in the test system for simulating the detection performance of the reference system. The following form of the radar equation was employed:

$$P_a = \frac{K \, (4\pi)^3 \, \tau_c \, B_n \, N_o \, (PRF) \, R_s^4 \, (\frac{S}{C+N})_n \, L}{G^2 \, \lambda^2 \, S_i(n) \left[ \sigma_T - \frac{\sigma_c \, (\frac{S}{C+N})_n}{S_i \, (n_c)} \right]} \qquad (A-8)$$

In order to convert to pulse power, which is the parameter we wish to monitor in the test-bed system, the following supplemental equation is used:

$$P_p = \frac{P_a}{\tau_c \, (PRF) \, (PCR)} \qquad (A-9)$$

The symbols in these equations have the following definitions and values:

$P_a$ = average transmitter power, watts

$P_p$ = pulse power in Kw which corresponds to the calculated average power

$K$ = (1852 meters/nautical mile)$^4$

= 11.76424 x 10$^{12}$

$(4\pi)^3$ = 1.98440166 x 10$^3$

$B_n$ = receiver noise bandwidth, Hz

$\tau_c$ = compressed pulselength, seconds

$\tau_c B_n$ = 1

(PRF) = the pulse repetition frequency, pulses/sec

= 39.0 pps for the shallow-grazing-angle subsystem

= 62.5 pps for the steep-grazing-angle subsystem

$N_o$ = receiving system noise power per unit bandwidth, watts per Hz. See previous discussion of this parameter.

$R_s$ = radar slant range, n.mi. This parameter is an incremented variable.

$(\frac{S}{C + N})n$ = integrated signal-to-clutter plus-noise ratio required for a probability of detection ($P_d$) of 0.90 for fluctuating targets, and a probability of false alarm ($P_{fa}$) of 10$^{-10}$. This ratio is a function of integration time. In the computer program the required value of signal-to-clutter-plus noise ratio is calculated from equations based on Fig. 10 of Ref. 2.

$L$ = system transmitting losses. See Table A-1.

G     =   antenna gain.  Refer to previous discussion of
          this parameter.

$\lambda$     =   wavelength, meters

      $\approx$   0.24373   (1230 MHz)

$S_i(n)$  =   integration improvement factor.  The following
          equations are approximations to a curve in
          Introduction to Radar Systems by M. I. Skolnik.
          These equations give values for the integration
          improvement factor when n pulses are integrated.

$$S_i(n) = 1.01\, n^{0.944} \qquad 1 \leqq n < 4$$
$$= 1.282\, n^{0.775} \qquad 4 \leqq n < 20$$
$$= 1.675\, n^{0.688} \qquad 20 \leqq n < 100 \tag{A-10}$$
$$= 2.59\, n^{0.593} \qquad n \geqq 100$$

in which

$$n = (\theta/\omega)\ (\text{PRF}) \tag{A-11}$$

where

      $\theta$   =   effective azimuth beamwidth in
                radians as given by Eq. (6) in the text.

      $\omega$   =   rotational velocity of the antenna,
                rad/sec

$\sigma_T$   =   the average cross section of a fluctuating target
          in square meters

      =   200 square meters in this analysis

$\sigma_c$   =   effective radar cross-section of sea clutter within
          a resolution cell

$$= \sigma^\circ\ K_1\ R_s\ \theta\ \frac{c\ \tau_c}{2}\ \sec \phi \tag{A-12}$$

in which:

$\sigma^{\circ}$ = backscattering coefficient of the sea, which is dependent on frequency and grazing angle.

$K_1$ = $3.429904 \times 10^{5}$ $m^2/(nmi)^2$

$R_s$ = slant range, nmi

c = speed of light

= $1.61875 \times 10^{5}$ nmi/sec

$\phi$ = grazing angle at the earth's surface

= $\arccos \left( \dfrac{\cos \psi \, (r_e + h)^*}{r_e} \right)$     (A-13)

where:

$r_e$ = earth radius

= 3440.0 nmi

h = aircraft altitude, nmi

$\psi$ = depression angle measured at the radar platform.

$S_i(n_c)$ = modified integration improvement factor to account for partial correlation of sea clutter. When the product of the decorrelation time (Td) and pulse repetition frequency (PRF) is less than unity (i.e., no correlation between pulses), $S_i(n_c) = S_i(n)$ as given in Eq. (A-10). When Td x (PRF) $\geq$ 1 (i.e., partial correlation between pulses), determine $S_i(n_c)$ from Eq. (A-10) with:

* The derivation of Eq. (A-13) is shown in Appendix B.

$$n_c = n/(Td(PRF)) \qquad\qquad (A\text{-}14)$$

where:

$Td$ = decorrelation time

$\quad = \lambda/(\theta\, V_t) \qquad\qquad (A\text{-}15)$

$V_t$ = velocity of aircraft

$\quad = 311$ feet/sec

PCR = pulse compression ratio

$\quad = 200$

## APPENDIX B

## DERIVATION OF EQUATIONS FOR DEPRESSION ANGLE AND GRAZING ANGLE

To obtain the desired tabulation of r.f. power levels using the radar equation, it is necessary to calculate grazing angle for any given value of radar altitude and slant range. Fig. B-1 shows the geometry for a radar at altitude h illuminating a target at radar range $R_s$. The target lies at a grazing angle $\phi$ with respect to the ray from the radar. This same ray makes an angle $\psi$ with the local horizontal plane at the radar. $\psi$ is called the depression angle. $\alpha$ is the angle subtended by the radar and target at the center of the earth.

By the law of cosines:

$$\cos \psi_x = \frac{(r_e + h)^2 + R_s^2 - r_e^2}{2 (r_e + h) R_s} \tag{B-1}$$

$$\psi_x = \arccos \left( \frac{(r_e + h)^2 + R_s^2 - r_e^2}{2 (r_e + h) R_s} \right) \tag{B-2}$$

However,

$$\psi = 90 - \psi_x$$

Therefore,

$$\psi = \arcsin \left( \frac{(r_e + h)^2 + R_s^2 - r_e^2}{2 (r_e + h) R_s} \right) \tag{B-3}$$

Next, applying law of sines to Fig. B-1, we obtain the following:

$$\frac{R_s}{\sin \alpha} = \frac{r_e}{\sin \psi_x} = \frac{r_e + h}{\sin (90 + \phi)} \tag{B-4}$$

Since $\psi_x = 90 - \psi$, Eq. (B-4) can be written as

$$\frac{r_e}{\sin (90 - \psi)} = \frac{r_e + h}{\sin (90 + \phi)}$$

in which the first term of Eq. (B-4) has been dropped.

Then, by the trigonometric identity $\sin (90 \pm x) = \cos x$:

$$\frac{r_e}{\cos \psi} = \frac{r_e + h}{\cos \phi} \qquad \text{(B-5)}$$

Solving this equation for the grazing angle, we obtain:

$$\cos \phi = (1 + h/r_e) \cos \psi$$

$$\phi = \arccos \left( (1 + h/r_e) \cos \psi \right) \qquad \text{(B-6)}$$

In the computer program for calculating r.f. power, Eq. (B-6) is used in conjunction with Eq. (B-3) to determine the grazing angle for selected increments of altitude and range. Using these values of grazing angle, the radar equation is solved as outlined in Appendix A to obtain values of radar pulse power.
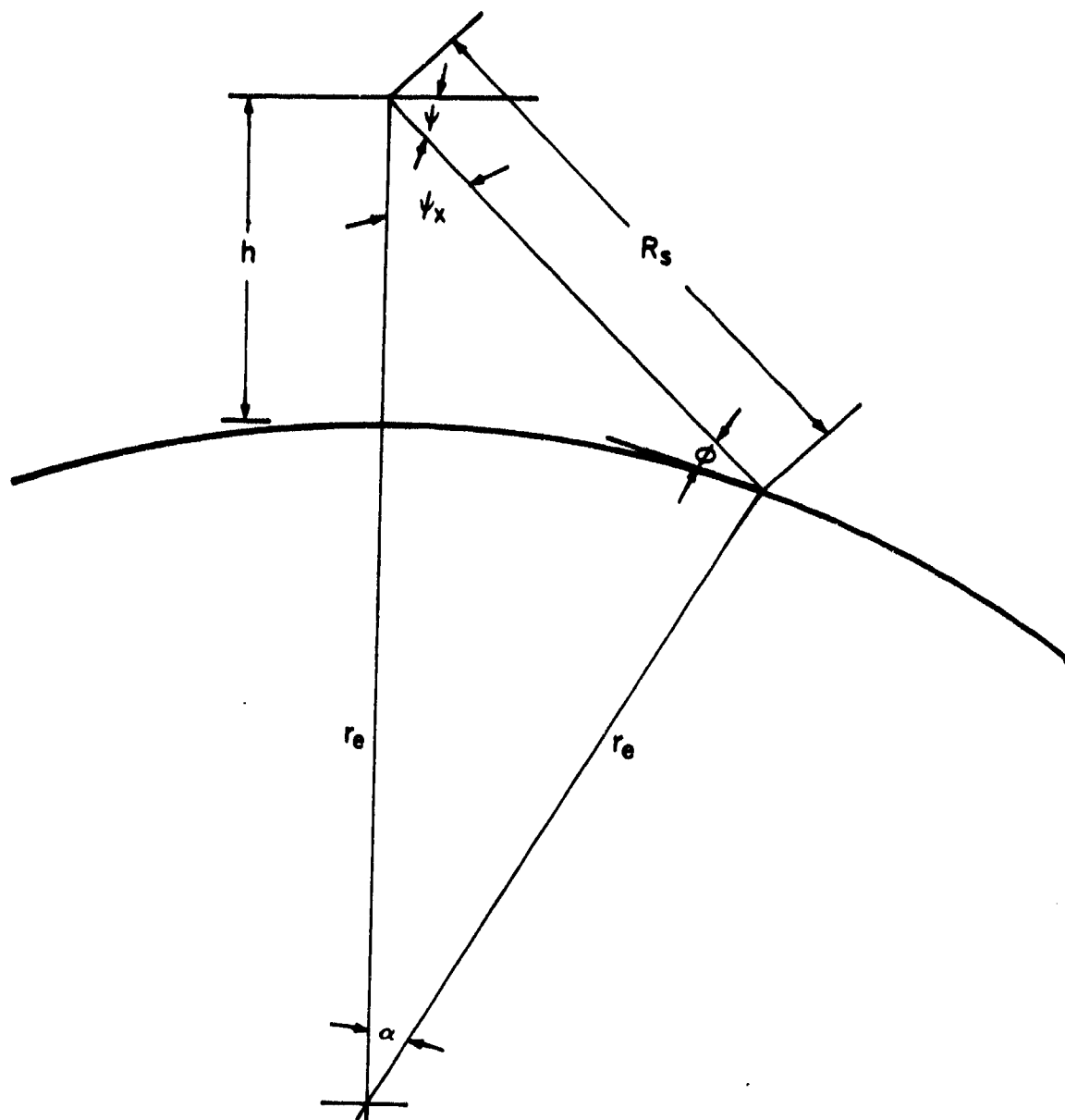
Fig. B-1 -- Geometrical relationships between grazing angle, ( $\phi$ ),
depression angle ( $\psi$ ), radar altitude (h), and slant range ( $R_s$ ).
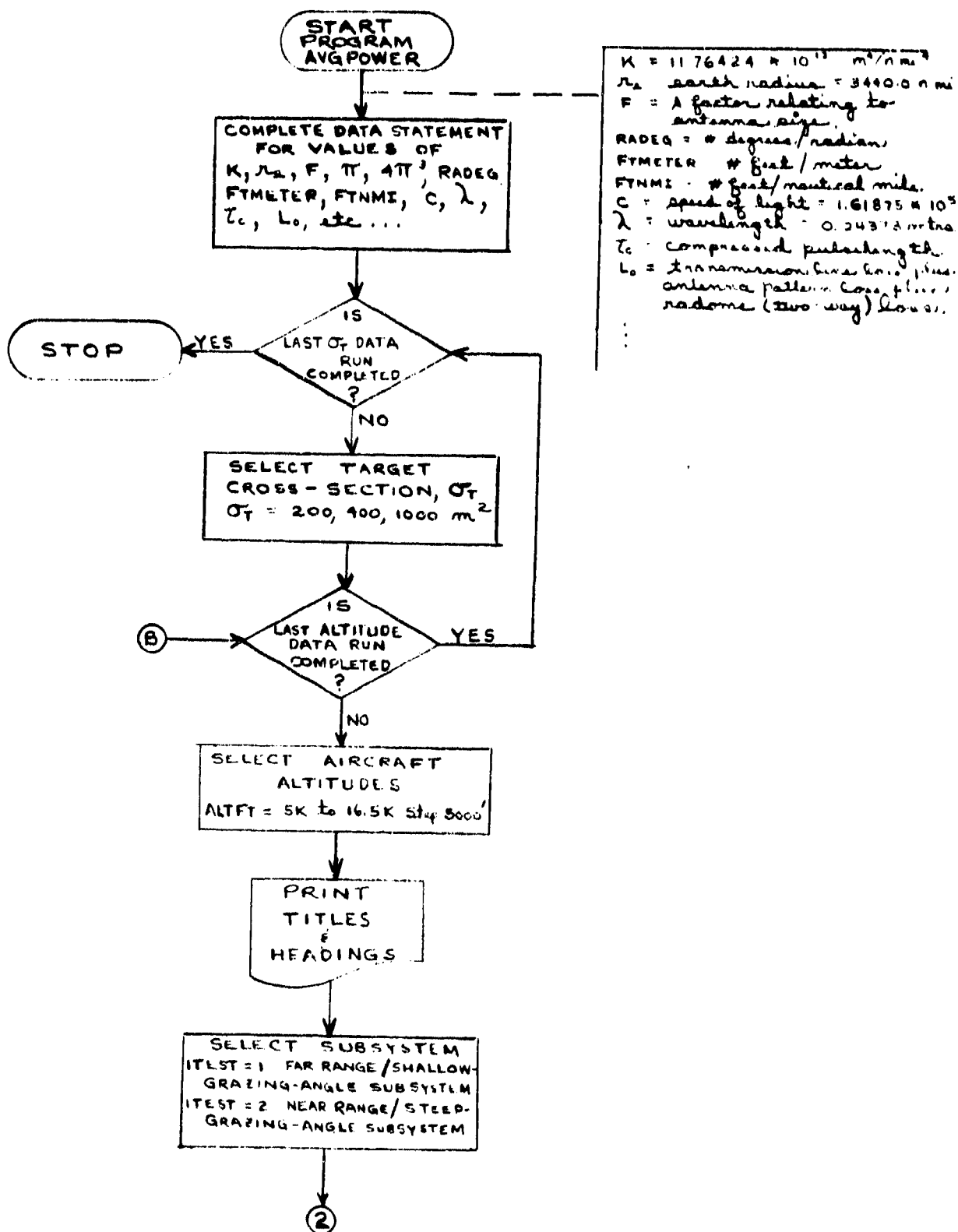
APPENDIX C

FLOW CHART OF THE COMPUTER PROGRAM
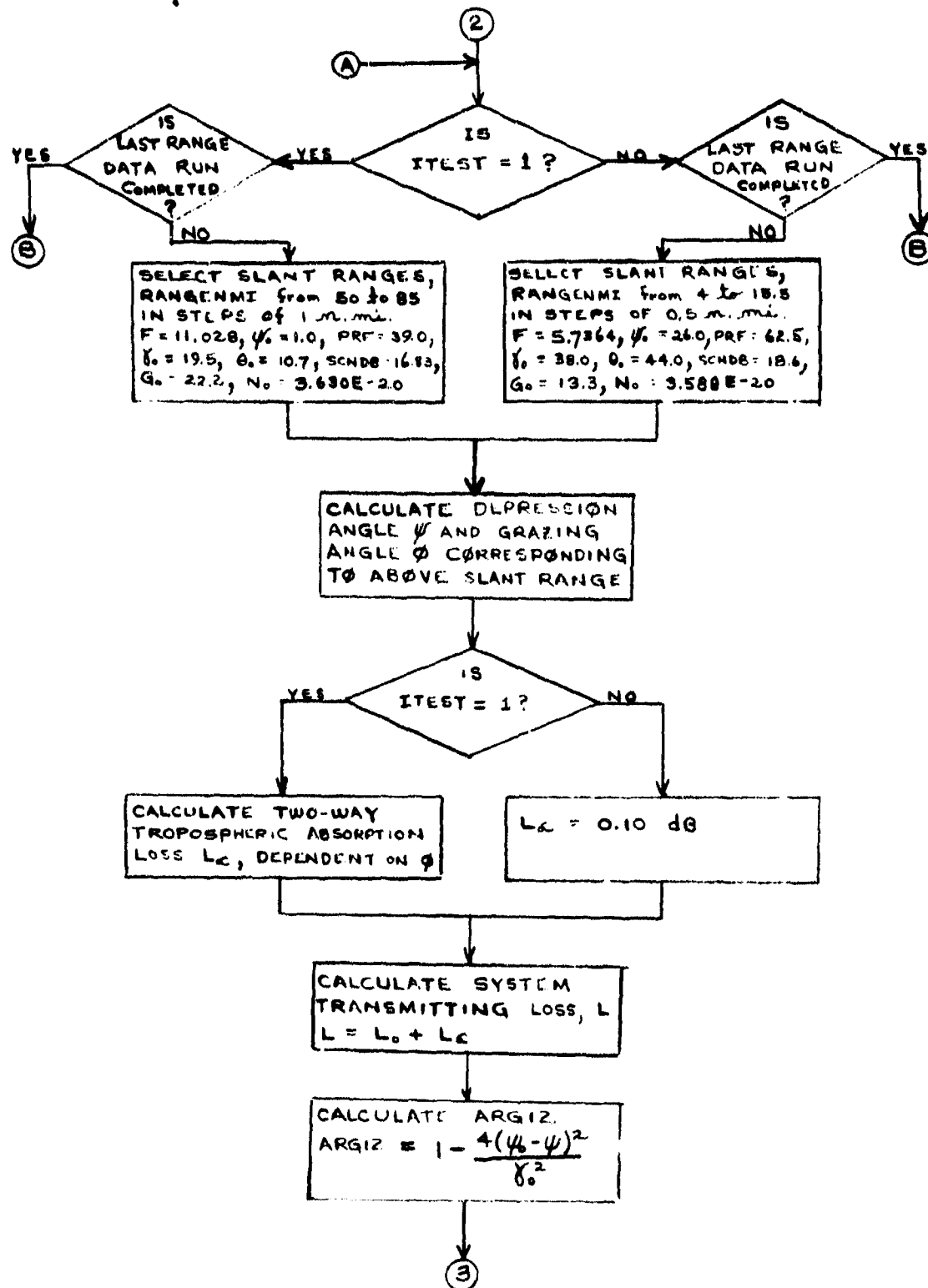FOR CALCULATION OF R.F POWER

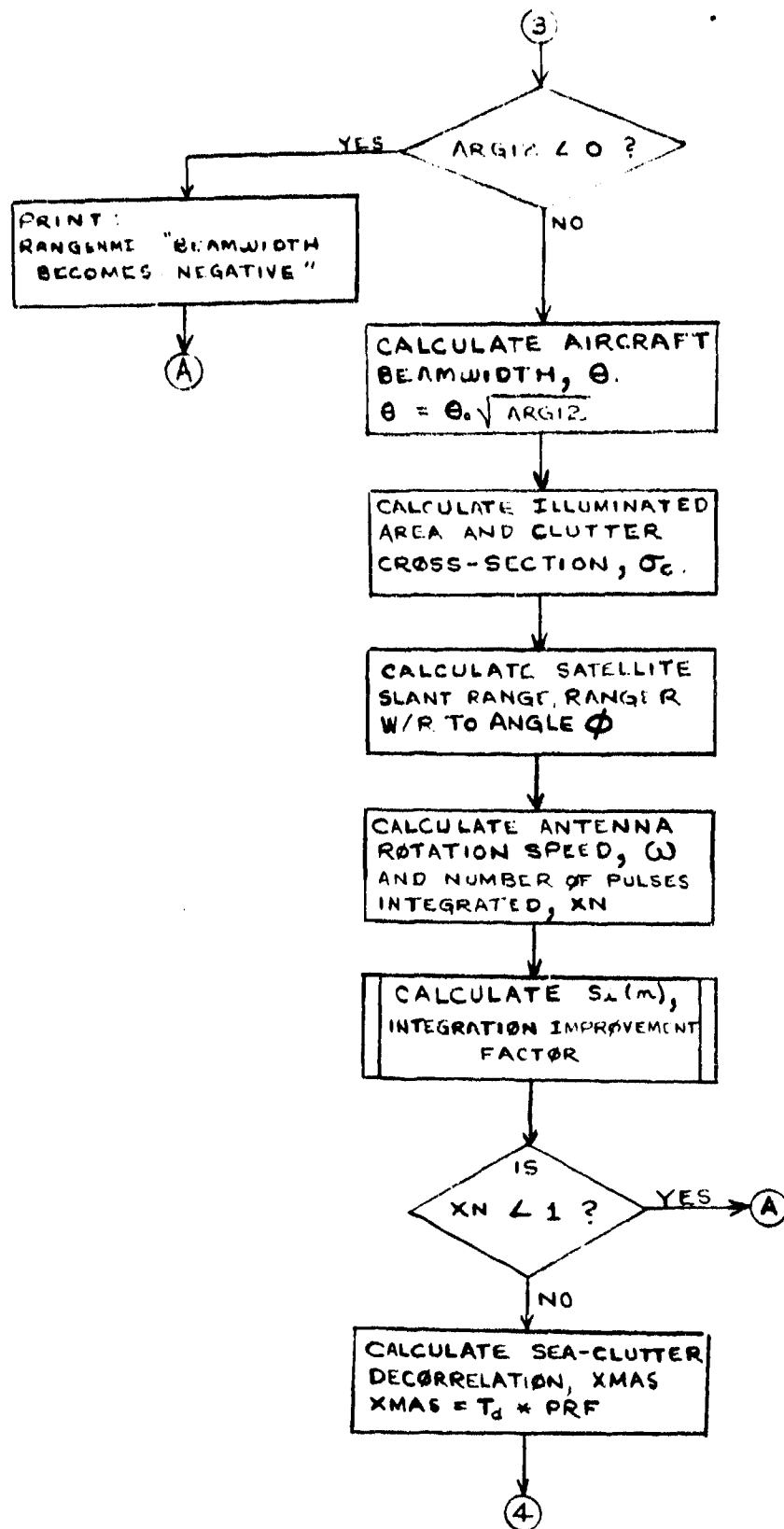Fig. C-1 - Computer program flow chart

Fig. C-2 – Computer program flow chart (continued)
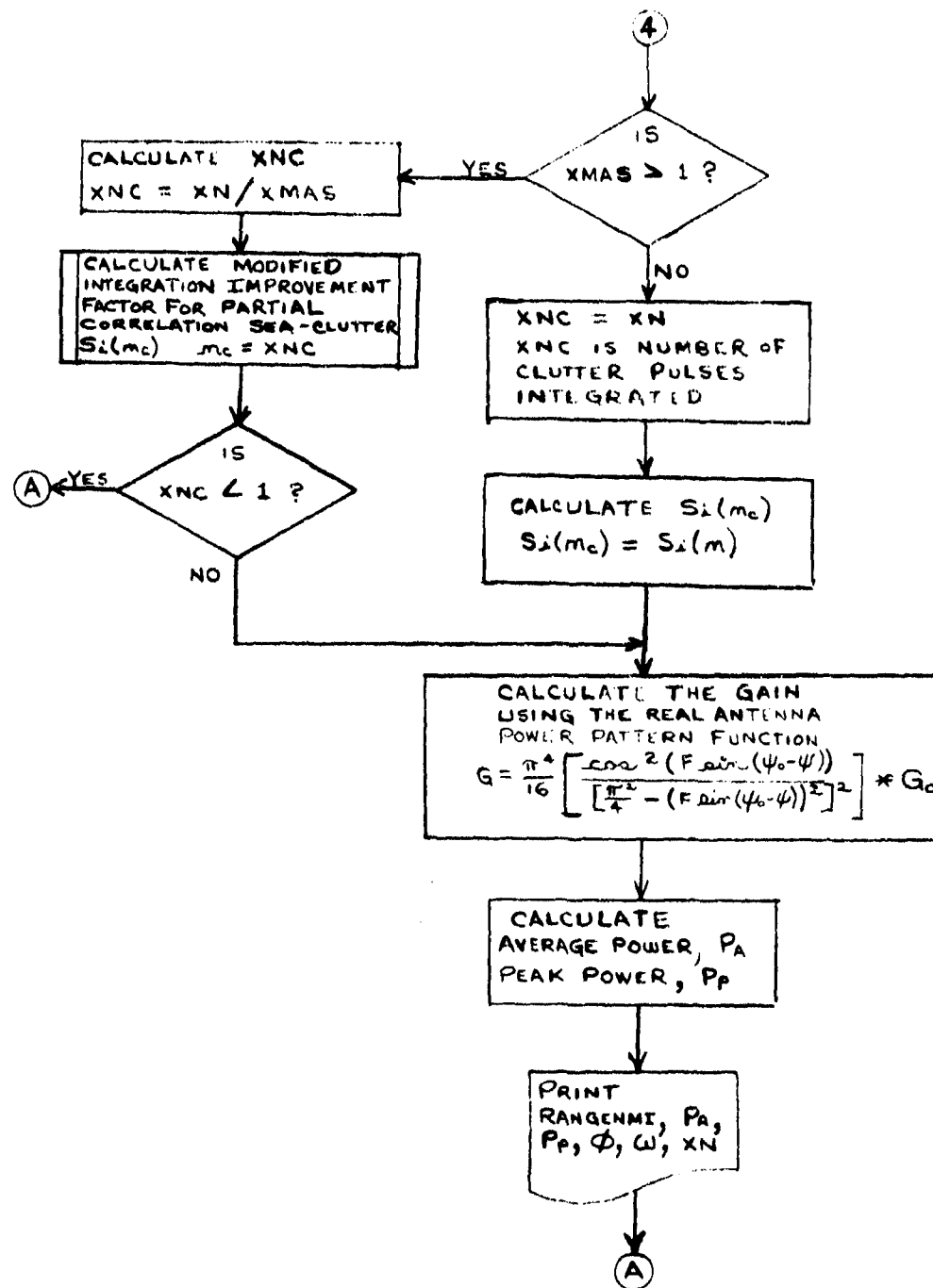
Fig. C-3 – Computer program flow chart (continued)

Fig. C-4 - Computer program flow chart (continued)

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    Of Lossy, Symmetrical Dielectric Radome Sandwiches", NADC-EL-
    52188 (Unclassified Report), October 22, 1953

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13. ABSTRACT

(S)  A scaled radar test-system is being flown in an EC-121 aircraft to
investigate some of the problems associated with ocean surveillance.  This test-
system has been scaled so that its performance will simulate that of a satellite-
borne ocean-surveillance radar orbiting at an altitude of 200 nautical miles.  This
report provides some operational guidelines which will aid in obtaining meaningful
data from the system.  Curves and charts are presented which will: (1) permit the
selection of grazing angle; (2) indicate the properly-scaled values for antenna
rotation rate and transmitter power; and (3) show the limits of operation as a
function of radar altitude and target range.

| | KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|---|
| | | ROLE | WT | ROLE | WT | ROLE | WT |
| | Radar surveillance | | | | | | |
| | Ocean surveillance | | | | | | |
| | Radar test system | | | | | | |
| | Airborne radar | | | | | | |
| | Scaling | | | | | | |
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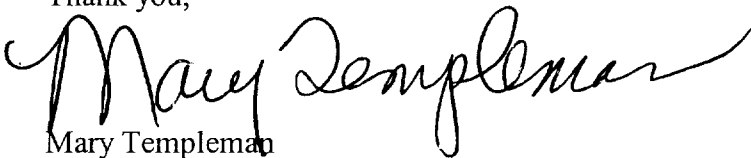**CC:**        Tina Smallwood, Code 1221.1 *12 6/21/02*

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--23 - DESCRIPTORS: (*RADAR, AIRBORNE), TEST EQUIPMENT, TEST
-- FACILITIES, MODEL TESTS, SCALE, SIMULATORS, TEST METHODS, ALTITUDE,
-- RANGE(DISTANCE), RADAR TRACKING, EFFECTIVENESS
--24 - DESCRIPTOR CLASSIFICATION: UNCLASSIFIED

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--29 - INITIAL INVENTORY: 2
--32 - REGRADE CATEGORY: C
--33 - LIMITATION CODES: 3
--35 - SOURCE CODE: 251950
--36 - ITEM LOCATION: DTIC
--38 - DECLASSIFICATION DATE: OADR
--40 - GEOPOLITICAL CODE: 1100
--41 - TYPE CODE: N
--43 - IAC DOCUMENT TYPE:
--49 - AUTHORITY FOR CHANGE: S TO C GP-3